Usability and Design of Personal Wearable and Portable Devices for Thermal Comfort

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Usability and Design of Personal Wearable and Portable Devices for Thermal Comfort in Shared Work Environments

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Personal comfort is important in the design of objects and environments. However, as comfort is a subjective experience, it is a very difficult aspect to design for. This paper presents an interrogation into the design for human thermal comfort, in particular the design of personal devices for use in shared work environments. The findings of two user studies are presented, in which wearable and portable, off-the-shelf personal heating and cooling devices were deployed in the field to explore the interaction with and use of these devices in everyday settings with the aim to uncover key aspects and requirements for the design of such devices. We found that functionality and affordances, i.e. the design for versatility, appropriation and mobility, as well as control, availability, effectiveness and efficiency of use were most important. Furthermore, individual preferences, foremost the preference for on-body versus off-body heating and cooling, and aspects related to wearable design of the devices, such as aesthetics, materiality, comfort of wear, mobility and unobtrusiveness, also need to be taken into account.

User-Centred Design. Interaction Design. Individual Thermal Comfort. Wearables. Affordances.

1. INTRODUCTION

Many human everyday actions and decisions centre on the achievement and provision of thermal comfort (Humphreys 1995; Shove 2003): whether it is adjusting the thermostat or opening the windows, or choosing an outfit for comfort throughout the day. Although, standards exist, which describe zones of comfort for indoor environments, the perception of comfort and what is comfortable remains highly subjective (ASHRAE 2013).

Comfort is a subjective and dynamic state influenced by a multitude of factors, which make it a very difficult aspect to design for (de Dear & Brager 1998; Vink, Overbeeke, et al. 2005). At the same time comfort is a requisite, as it affects the performance and well-being of human beings. Poor design of environments and poor indoor environmental climates can lead to health issues, reduce productivity and satisfaction (Leaman & Bordass 2005a; Vink, Overbeeke, et al. 2005).

Problems with the achievement of individual comfort arise especially in shared environments such as open-plan offices, in which the level of control available to the individual and consequently the possibilities to adjust local environmental parameters according to one's own needs are limited. Although the positive effects of perceived control and in consequence the provision of personal environmental control systems on perceived comfort and productivity are known, this form of indoor environmental control is not very widespread (de Dear et al. 2013).

Research into wearable and portable solutions for personal thermal comfort can address individual needs by shifting focus from global to individual and static to mobile provision of comfort in shared spaces. However, previous research in the area of wearable heating and cooling garments, for example, has mainly addressed applications for extreme conditions or special use cases and focussed accordingly on the effectiveness and efficiency of the solutions (Wang et al. 2010; Yazdi & Sheikhzadeh 2014). With a constantly growing range of wearable and portable heating and cooling devices and aids for personal use available on the market, we argue that questions of usability and design of personal thermal devices in their context of use require closer examination: how users interact with these devices in context, how these devices respond to user needs and how this can lead to the formulation of design requirements.

This paper presents the findings of two small-scale user studies in the field, in which we evaluated personal, off-the-shelf devices for heating and cooling in open-plan offices. The aim of the studies was to uncover aspects involved in the use, usability, application and design of wearable, portable solutions for personal thermal comfort leading to the formulation of design requirements and recommendations tailored to the context of use. The user-centred, inductive approach we followed incorporated existing frameworks and methods both from human computer interaction (HCI) and thermal comfort research.

2. BACKGROUND

The paradigm shift from a physical, steady-state and deterministic model of comfort to an adaptive and holistic comfort model has been identified as one of the most important and significant developments in thermal comfort research in the past twenty years (de Dear et al. 2013). The adaptive comfort model pays attention to the fact that people are not merely physiologically responding to the thermal sensations experienced in an environment at a certain point in time but that more complex mental and adaptation processes are taking place with which people achieve comfort (Brager & de Dear 1998; de Dear 2004). The perception of comfort is not only influenced by a multitude of external and internal factors, such as clothing, activity level, constitution, health and gender, environmental characteristics and sensory input, but it is also overlaid by expectations, emotions and past experiences (de Dear & Brager 1998; Vink, Looze, et al. 2005; Hellwig 2009; Kingma & van Marken Lichtenbelt 2015). Comfort is a dynamic state that evolves out of the lived and embodied experience of a person in relation to their surroundings and is therefore highly subjective. Accordingly, thermal comfort has been defined as:

> "that condition of mind that expresses satisfaction with the thermal environment" ASHRAE Standard 55 in (ASHRAE 2013, p.9.1).

Any deviation away from an individual optimum level of thermal comfort leads to affective, cognitive and behavioural responses. These processes of adaptation have been defined as: physiological, i.e. by acclimatisation, behavioural, i.e. by interacting with and changing the environment, for example, by opening windows or adjusting HVAC settings, or by changing personal aspects, such as clothing, and psychological, i.e. by habituation, e.g. through adjusting expectations (Brager & de Dear 1998; Parsons 2003). Climate, building design, social organisation, tasks and occupation, regulations or economic reasons can place constraints on behavioural adaptation and the actual context can thus determine how much control and adaptive opportunities are available (de Dear & Brager 1998).

However, research has stressed the importance and impact of perceived control in regard to the perception of thermal comfort. It has been shown that the amount of perceived individual control over related environmental parameters is more important than the actual environmental state and impacts perceived comfort, satisfaction, perceived health and productivity (Leaman & Bordass 2005a; Leaman & Bordass 2005b; de Dear et al. 2013). Research into personal environmental control (PEC) or task ambient conditioning (TAC) systems has consequently been identified as one of the key areas for further research (de Dear et al. 2013). Besides increasing perceived individual comfort, studies suggest that PEC or TAC systems could also help reduce energy consumption due to low power and local instead of global application (Zhang et al. 2008). Although PEC and TAC building solutions such as directed vents and outlets exist, they are not widespread (IFMA 2009).

These findings suggest that micro-climates at a local, personal level pose a potential area of further investigation in the field. With rapid developments taking place in the portable and wearable technologies sector, this investigation can be taken beyond what PEC systems can provide. Wearable or portable solutions for thermal comfort can be used independently of spatial considerations and comfort can be provided where it is needed: at a personal, local level, to some extent independent of but always in relation to the local climate.

Research and development of wearable and portable personal micro-climates have so far been conducted primarily in respect to applications for extreme conditions, such as under water, outer space, in extreme heat or cold, and for special use cases, such as sports, medicine, military or thermally stressful workplaces (McCarty 2005; Yazdi & Sheikhzadeh 2014; Heller & Grahn 2012). In addition, the main focus of enquiry lay on the effectiveness and efficiency of the solutions to alleviate heat or cold stress of the users (Wang et al. 2010; Yazdi & Sheikhzadeh 2014). However, applications in extreme or hostile environments present different challenges for personal thermal solutions compared to non-extreme, every-day conditions. Current commercial solutions for individual thermal comfort target audiences and application areas such as health and well-being, outdoor activities and sports (Walker 2013). The Wristify, a mixture of well-being and lifestyle device, is still under development (embr labs 2015).

Wearable systems provide new challenges for design, as they require a new set of gestures for interaction and the body-centred development for comfort and contextual suitability while taking opportunities, characteristics and limitations of materials and technology into account (Benyon 2014). Furthermore, Chan et al. (2012) identified user acceptance and in consequence the design of useable devices that address the users' needs as one of the ongoing challenges in the development of wearable technologies and as an essential aspect towards their endorsement by the users. Rogers et al (2011) define the following key issues to be taken into account in the design of wearables: comfort, hygiene, functionality, usability, privacy and social acceptance. The most important factor in regard to usability is control, i.e. the answer to the questions of how and what the user can control using which modalities (Rogers et al. 2011).

Comfort in the design of a wearable and portable device has been attributed to its being non-obtrusive, light and small as well as invisible (Rogers et al. 2011). According to Vink, Looze, et al. (2005), however, comfort cannot be attributed to an object but instead arises out of its use. As a "subjective phenomenon" (Vink, Overbeeke, et al. 2005, p.8), it cannot be easily be predicted and can in the scope of the experience of an object or environment only be evaluated by the persons using it in a setting which resembles the real life context as closely as possible (Vink, Overbeeke, et al. 2005; Vink, Looze, et al. 2005).

We concluded from the review of previous research in the area that aspects surrounding the interaction with and use of personal thermal devices in everyday settings have not received particular attention yet. Although, challenges in the design of wearable systems have been described, the question remained: how can these be applied to the specific context of use to prove and improve their validity? As the interest of our enquiry lay in individual thermal comfort in shared work environments and as a wide range of commercial personal heating and cooling solutions were already available, we chose an inductive research design to approach the topic: deriving design requirements and usability aspects surrounding the design for thermal comfort bottom up, evolving out of the use of the devices in context.

3. METHODOLOGY

In the scope of two small scale user studies we looked at the usability of off-the-shelf personal heating and cooling devices and the challenges of their use involved in the context of shared open-plan work environments. The studies took place over the course of four weeks respectively. The study on personal heating devices took place in March 2015, with average recorded temperatures at participants' desks ranging from 20.7°C to 28.4°C. The study on personal cooling devices was conducted in July 2015, with recorded average temperatures at participants' desks ranging from 22.2°C to 29.8°C. Median average temperatures are 23.9°C for study 1 and 26.5°C for study 2. The temperature recordings varied with outdoor conditions and across participants due to the location and local characteristics of their workplace, such as sitting next to a heater or window.

3.1. Selection of Devices

The devices used in the scope of the studies were selected for their different properties in regard to size, affordances and body locations they could be applied to.

For the study on personal heating, we selected commercially available heated gloves (Mobile Fun Limited 2015), a heated shoulder pad (Beurer GmbH 2015), heated socks (blazewear 2014), a hot water bottle (E-Bargain UK 2015), and a personal fan heater (De'Longhi UK 2015), all of which we equipped with a temperature sensor and XBee radio circuit to transmit device temperature information (fig. 3.1). Apart from the hot water bottle, which was filled with hot water by the participant, all other personal heating devices featured heat pads or heat strings to provide heat and either ran on battery or had to be plugged into USB or mains.

Figure 3.1: *Personal Heating Devices, clockwise from top left: personal fan heater, heated socks, heated shoulder pad, heated gloves, and hot water bottle.*

The off-the-shelf devices we deployed in the cooling study were a personal cooling fan (Cool on the Go 2015), wrist coolers, ankle coolers, a cooling body wrap, and a cooling neck tie (Polar Products 2015) (fig. 3.2). The latter three devices were equipped with a temperature sensor and XBee radio circuit to transmit device temperature information. Apart from the cooling fan, which ran on batteries and USB, the remaining cooling equipment used ice packs for cooling, which were provided by us for each day of the study.

Figure 3.2: *Personal Cooling Devices, clockwise from top left: cooling body wrap, cooling neck tie, wrist cooler, personal cooling fan, and ankle coolers.*

Each device was tested by two participants during the studies. The cooling neck tie and the wrist coolers were tested by three participants.

3.2. Participants

Participants were recruited among PhD students and postdocs at the School of Electronic Engineering and Computer Science at Queen Mary University of London. Participants worked in open-plan offices in either the Engineering Building or the Computer Science Building. For the heating study six (three female, three male) participants were recruited and eight (five female, three male) participants were recruited for the cooling study. The number of participants testing devices was limited to five at any one time due to the number of available devices and sensors.

3.3. Study Approach and Set-Up

The studies followed an inductive, user-centred approach which incorporated existing frameworks and methods both from HCI, and thermal comfort research. To uncover and retrieve information on the use and usability from the lived experience of the users, we deployed the off-the-shelf devices for personal heating and cooling in the wild, i.e. to participants at their workplaces.

In the studies we incorporated long-term comfort questionnaires, a research tool used in post occupancy evaluation (POE), to evaluate the satisfaction of the occupants with their environment, as well as right-now surveys and environmental data collection, tools used in thermal comfort research, to establish human thermal comfort at a certain point in time (Peretti & Schiavon 2011). In addition, we used evaluation questionnaires to retrieve feedback on the use and usability of the devices, which are commonly used in design evaluation (Rogers et al. 2011).

In the first part of each study, the general perceived comfort of participants was assessed. Participants filled out a questionnaire on their long-term comfort to indicate their satisfaction with a range of indoor environmental factors, how they used the space, how comfortable they felt and how they adapted to their thermal environment in order to ensure their individual thermal comfort in the space.

In the second part, participants were given one of five devices, which provided local warmth or cooling to help improve their perceived personal thermal comfort in the shared work environment. We allocated the devices according to availability and so that ideally each device was tested by male and female participants. Each device was given to a participant for three working days. During this time, participants filled in right-now questionnaires, in which they were asked to record how they felt and how they would like to feel thermally at that point in time as well as to indicate any changes to clothing. Participants were asked to fill in the questionnaire two to three times a day: shortly after coming in, before or after lunch, and mid-afternoon. Due to flexible working hours, the actual recorded times varied between participants. In addition, the environmental conditions at each participant's workplace were recorded using locally networked sensor nodes. These detected temperature and/or humidity, light levels as well as wind speed to detect draughts. The sensor nodes stayed installed over the whole period. To record the duration of use as well as the surface temperature of the devices, we asked the participants to switch on the sensing circuit on the devices during their use. However, not all incidents of device use could be recorded, as devices were sometimes out of reach of the base station, participants forgot to switch on the wearable sensor or data drops occurred.

After each episode we asked participants to provide us with feedback on their device use and its perceived usability. The device evaluation questionnaires consisted of mainly open-ended questions, which also covered behavioural adaptations, perceived changes in comfort when having the devices, and suggestions for alterations. This was combined with a questionnaire at the end of the study reflecting on participants' more general expectations, suggestions and preferences in regard to personal heating or cooling devices.

For data analysis, we used an inductive approach to develop themes out of the qualitative data we collected. The data was coded by the researcher following the steps proposed by Braun and Clarke (2006) for thematic analysis. The coding took place in two iterations to review and verify the themes.

4. FINDINGS

The findings obtained from the feedback of the participants in regard to their experience using the devices in their work environment are described separately for the heating and the cooling devices study. The contributions of individual participants are coded anonymously and are attributed by the abbreviations H1 to H6 and C1 to C8 respectively.

4.1 Findings from the Use of Personal Heating Devices

In the following we present the qualitative findings from the user feedback, which can be thematically grouped into four main areas: usability, perceived affordances, wearability and individual preferences and context of use.

4.1.1. Usability: Aspects of Effectiveness, Efficiency, Availability and Control

The effectiveness of devices was related to their ability to provide as much heat as was needed, when needed, and where needed. It depended on the technology involved and how much heat it could provide but also on the users' perception at the receiving end. For example, the amount of heat provided by the heated gloves was according to different users either sufficient (H4) or poor (H2). For the heated socks users mentioned that they became too hot (H1) or the heat became too much when the participant forgot to switch them off (H6).

The inability to provide the right amount of heat could lead to dissatisfaction with the device. Both participants using the fan heater reported that the fan heater provided too much heat (H1, H5). One of the participants stated:

> "The device I did not enjoy using was the personal fan heater, because that device made the air too hot most of the time" (H5).

For the fan heater both participants using it also reported problems and their frustration with the heat adjustment due to interface design issues. They could not tell from its interface how the setting of the thermostat related to the actual room temperature. The heater would stop unexpectedly if this unknown temperature had been reached.

Control, i.e. the ability to adjust the strength of the heating as required, was reportedly a key aspect in addressing and increasing the usability of the devices. It was addressed by four participants in the study. The lack of different heat settings was reported negatively for the fan heater (H5) and the heated socks (H6). In turn, the choice of settings and consequently amount of control provided was reported positively for the heated shoulder pad (H3, H5), which featured five different heat settings:

> "I enjoyed using the heated shoulder pad because it made me warm in the amount I really needed" (H3).

Accordingly, two participants mentioned adjustable temperature as something they would wish for in a personal heating device (H3, H4). In addition, one of the participants mentioned to offer the possibility of providing automatic control based on the body temperature alongside manual control (H3).

Also the ease of use of the device but in particular the ready availability of the heat was important. Ready availability was positively reported for the heated shoulder pad (H3). In contrast, a participant (H4) noted in respect to the hot water bottle that she did not like having to leave the office to heat water and in consequence decided not to use it. The effort of doing so exceeded the benefit she was expecting to receive in return. The second participant (H2) using it also reported difficulties, such as finding the right sink and sufficiently hot water. Electrical solutions possessed an advantage in this regard, as they were available immediately.

Participants reported different patterns of use. Two participants used the devices they were given in the mornings, after having sat at the desk for an hour (H2, hot water bottle and gloves) or shortly after coming into the office to jumpstart thermal body regulation after cycling (H6, heated socks). Another participant (H1) stated using the socks often in the evenings and the fan heater whenever needed. Two participants started but then stopped using the devices (H3 for fan heater and shoulder pad, H4 for heated gloves) or did not use them at all (H4, hot water bottle). The average recorded duration of use of the heated gloves, the heated shoulder pad, and the personal fan heater ranged in between 46 and 48 minutes compared to 114 minutes for the heated socks. Recorded individual uses of the gloves, shoulder pad, and fan heater ranged between 5 minutes up to 1.5 hours and up to 5 hours for the socks. Only one incident of use was recorded for the hot water bottle at 87 minutes.

4.1.2. Perceived Affordances: Body Location, Versatility and their Impact on User Appropriation, Adaptation and Satisfaction

We found that other key aspects in the use of the heating devices included the area of use, i.e. the body location the device covered and to which heat was applied to, and how flexible and easy to appropriate a device was. Some of the devices, such as the heated gloves, socks and shoulder pad, were designed for use on a certain body part, which limited their versatility and the possibilities of appropriation. But devices were well received if their application area coincided with comfort issues such as cold feet. Accordingly, the users of the heated socks reported positively on their use of this device (H1, H6). One participant liked the idea of heated socks and stated that it would be the device he would wish for (H1). Perceived effectiveness and efficiency of use were inhibited if a device did not deliver the right amount of heat to the right body location and did not allow for appropriation. For example, having the heat pad on the back of the hand did not feel as the right place to one user of the heated glove (H2). He suggested having the heat pad on the palm instead. This participant also mentioned that he was not sure how much the heat pads contributed to his comfort at all or if wearing the glove in general helped him feel warmer (H2).

The provision of heat to the right body parts kept reoccurring as a theme and was complemented by the appropriation and adaptation of devices by the participants. Both participants using the heated shoulder pad, appropriated the device (H3, H5). They used it on the shoulders and legs (fig. 4.2). Both reported positively on the appropriation but within limits: one participant reported that he suffered from cold feet at some point but that could not put the shoulder pad there (H5). The other user expressed her ideal heating device in accordance with her preference for the shoulder pad as follows:

> “thin and large enough to bend/fold for using on different body parts” (H3).

Figure 4.2: Appropriation of the heated shoulder pad.

In contrast to the wearable devices, the portable hot water bottle was not meant to be applied to a specific body location. Not knowing where to place it (H2) confused one user at first. Eventually, the participant appropriated his jacket to hold the hot water bottle and to provide warmth to his back.

Unlike with on-body devices, location-related aspects in the use of the fan heater addressed the body-environment relationship at large and the question of provision of heat on an environmental level. Although both participants experienced problems with the fan heater, they reflected positively on its advantages of being able to heat a larger area of space (H1, H5) and the possibility of applying it to different parts of the body (H1).

The preference and wish for a smart, non-wearable device was explicitly expressed by one participant (H5) in the study:

> “I would like a not wearable device that can predict how cold or warm I want to be, and then automatically the device would take decisions about how to change the environment temperature” (H5).

4.1.3. Wearability and Feel of Use: Implications of Material, Comfort of Wear and Mobility

Three participants reported that the materiality of the devices did impact the wearability and comfort of wear of a device they used. A negative impact was attributed to the material of the heated gloves, which was described as scratchy and which made them uncomfortable to wear (H4). The thickness of the cloth of the heated shoulder pad made one participant (H5) feel hot and required taking the device off. However, another participant reported positively on the comfort and smoothness of its cover (H3).

The wearability was also influenced by the heat generation method in place and the power supply it required. For example, the heat pad of the heated socks increased the thickness of the socks that had to be worn inside the shoes. Users stated in consequence that the heated socks were not comfortable to wear in the shoes (H1, H6). Furthermore, the battery packs of the heated socks provided a source of discomfort, as they had to be worn around the lower legs and were felt by the users as an obstacle (H6) and a burden (H1). They also came with a limited duration of use (H6). However, they did provide freedom of movement (H6). Drawbacks were also reported for other forms of power supply. For devices such as the heated gloves and the heated shoulder pad, which were powered externally using USB or mains, the wearability was reduced, as the cabling limited the mobility of the users. One participant reported:

> “cables, too short for me and once I lifted laptop off the table when stretching” (H2).

This and the fact that the controls dragged on the desk and caused an annoying noise led to behavioural adjustments on part of the participant (H2), which included wearing a long sleeved top so that he could put up the controls into his sleeves as well as the plugging in of the gloves into different devices to increase the range of movement. For the heated shoulder pad one participant (H3) reported the cabling as its only downside, because it made her feel desk-bound. Both users suggested a wireless version as possible improvement (H3, H5).

4.1.4. Individual Preferences and Context of Use

Overall two participants (H3, H5) mentioned the shoulder pad as the device they liked using the most. The heated gloves (H4) and the fan heater (H1) were each mentioned once in this respect. Two participants chose a fan heater as the least preferred device because it did not provide enough and direct heat to the body parts that felt cold (H5) or because the one provided by the school was too far away (H3). However, the fan heater was chosen as the device most convenient and useable in the workplace context by two participants because it could compensate for local discomforts such as draught from the window (H1) and it could heat up a larger area (H5). Although she decided for the shoulder pad as the most usable device in context, another participant (H3) stated that a fan heater was the more convenient one to use in general. She had to get familiar with the shoulder pad and to wearing something plugged into a power socket first (H3). One participant stated that of the devices she had been given the gloves were the most usable in context but that in general she preferred devices, which covered the back area.

4.2 Findings from the Use of Personal Cooling Devices

In the following we give an overview of the findings obtained from the user feedback on the use of off-the-shelf cooling devices, which addresses the areas usability, perceived affordances, wearability, individual preferences and context of use.

4.2.1. Usability: Aspects of Effectiveness, Efficiency, Availability and Control

As four out of five of the cooling devices employed during this study relied on ice packs for cooling, the issues reported by the participants on behalf of the usability of the devices and the effectiveness of their cooling occurred across the board. Four participants reported that it was too cold (C2, C4, C7) or the cooling effect was too strong (C3), which rendered the devices unusable at first (C4). However, adaptation processes occurred. Three participants either reduced the number of ice packs in use (C3) or they left the ice packs outside the cool box until they were less cold to wear (C2, C4). One user of the cooling body wrap stated:

> "I found it most pleasant to use with only one cooling pack and when placing it over my own belt for insulation, to diminish the cooling effect" (C3).

The effectiveness of the devices was criticised, as the ice-packs were not only too cold in the beginning but also lost their cooling effect over time, thus providing unstable cooling (C2, C7) and lacking temperature control (C7). One participant also mentioned that the cooling was uneven across the surface of the cooling neck tie (C7).

None of the issues mentioned above affected the battery/USB powered personal cooling fan, which provided a constant air flow while still offering flexibility of use, for example, by using it hand-held. However, a non-uniform air flow was criticised (C5). Furthermore, the effectiveness was reportedly very low (C1, C5). One user stated the air flow provided by the personal cooling fan could only marginally improve comfort but did not provide much cooling and relief from heat (C5). In addition, both users reported negatively on its noise (C1, C5).

Participants consequently mentioned stable cooling (C1) as well as covering a wider range of temperatures (C5) as functionalities they would wish for. In addition, participants expressed the wish to be able to control a cooling device remotely (C5) or via a mobile app (C8). This was combined with the wish for more discrete control:

> "Maybe have the choice to control the temperature from a mobile application to ensure discreteness" (C8).

Two participants discussed a smart device that would adapt to their body temperature (C2, C6):

> "It would be nice to have a temperature setting. Like a 'smart cooler' adjust the temperature based on people's body temperature" (C2).

Furthermore, participants commented positively on the lack of cables of the cooling neck tie (C4) and the personal cooling fan (C1). This, however, came at a price. In the case of the personal cooling fan it meant the fan did not have enough power (C1), which affected its effectiveness and functionality. For all other devices the ice packs had to be recharged in the freezer, which impacted their ease of use and the ready availability of cooling. As a participant stated, having had to get the ice packs from the fridge herself and putting them back after use would have greatly inhibited their use (C4). Jointly with the issue of instable temperature provision, this led to participants' suggestions to employ more permanent cooling packs (C1) and to look into other cooling techniques (C7).

The average duration of use was recorded for the ankle cooler at 62 minutes, for the cooling body wrap at 147 minutes, and for the cooling neck tie at 55 minutes. Individual recorded uses of the devices ranged in between 51 to 73 minutes for the ankle cooler, 27 to 4.75 hours for the body wrap and 2 minutes to 3 hours for the neck tie. No data was recorded for the wrist cooler and personal cooling fan, as the circuits did not fit on the devices. Five participants reflected on their use of the devices and reported that they either used the coolers after high activity, for example, after walking to the office (C4, C8), when they started work (C7) or during periods they felt hot (C1, C4, C6). Despite the temperature issues, the cooling pack based devices were reportedly more effective in relieving discomfort from heat and in cooling down the body. Five participants reported positively on the efficiency of cooling (C1, C2, C4, C7, C8). Users of the cooling neck tie, for example, stated:

> "the cooling neck tie really helped me to recover the comfort in hot days" (C1) and "good for cool down" (C7).

The wrist coolers were the only cool pack based cooling device for which insufficient cooling was reported (C1).

4.2.2. Perceived Affordances: Body Location, Versatility and their Impact on User Appropriation, Adaptation and Satisfaction

Six participants reported on the appropriation of devices, i.e. using them on different parts of the body, and on aspects of adaptation and flexibility of use. One of the users of the wrist coolers resorted to the ice packs themselves and used these on the skin without their textile cover (C1), whereas another user of the wrist coolers stated that she more often used them to cool down her palms than on her wrists (C6). For the ankle cooler, a participant (C2) noted she put it to her forehead and neck, not only around her ankles. Versatility was also attributed to the body wrap but not actively executed (C3). For the cooling neck tie participants reported to have also used it on the ears (C1) (fig. 4.2), the lap and around the ankles (C4). One participant stated:

> "I liked that it is flexible and that I can use it also at other body parts" (C4).

This participant also suggested increasing the flexibility of the tie further by adding a mechanism that would allow the length to vary.

Figure 4.2: Appropriation of the cooling neck tie.

4.2.3. Wearability and Feel of Use: Implications of Material, Comfort of Wear, Mobility and Obtrusiveness

Matters of wearability, which were brought up by participants, in particular regarded unobtrusiveness (C2, C8) materiality (C7), and aesthetics (C6, C7). Unobtrusiveness was addressed on a personal as well as a social level. One participant stated:

> "I like the fact it was personal so the change in temperature didn't have an impact on other people" (C8).

Aesthetic aspects were mentioned by two participants. One participant reflected critically on the appearance of the wearable cooling device she was given in the evaluation questionnaire, in which she stated that the device did not match her clothes (C6). Another participant suggested to develop something aesthetically more appealing (C7). This participant also criticised that the cooling neck tie she tested was not soft to wear (C7).

4.2.4. Individual Preferences and Context of Use

Overall, the cooling neck tie (C1, C2) and the personal cooling fan (C5, C7) were mentioned by participants as the devices they liked most. Four participants mentioned that they would find the personal cooling fan most usable and convenient in the context of their work environment (C1, C5, C6, C7), because it would not disturb others (C1, C7), it was easy to control and its orientation could be adjusted (C6). Although, a participant had reported that he could not use his hands properly at work when wearing the wrist coolers (C1), they were mentioned as the most usable and convenient device to use in context by him and another person (C1, C7). The cooling neck tie was only mentioned once in this regard (C2). Two participants reported that at times they had a fan turned on in addition to the cooling device given to them (C1, C2).

Two participants were sceptical of a wearable cooling device and expressed their dislike of having cooling in direct contact with their skin (C5) or their preference for more natural cooling in form of a water spray (C7). One other participant (C2), who had used the ankle cooler, expressed her dislike of putting cooling on her joints. She preferred an unobtrusive device, which would disappear in the environment or could be worn like a garment.

5. DISCUSSION

The findings of the two field studies contributed to our understanding of the use and usability of off-the-shelf personal heating and cooling devices in context and important uncovered aspects to consider in the design of such devices.

5.1. Discussion of Key Findings

The provision of stable and constant heating and cooling at the amount needed at a certain time has been found to be one of the key requirements regarding the effectiveness and control of personal heating and cooling devices. In addition to general personal and environmental characteristics, which affect perceived thermal comfort, the use of devices can also be attributed to metabolic rates and body temperature, which change over time and with different activities (Parsons 2003). Adjusting heating or cooling within a range of temperature settings would consequently allow the user to respond more effectively to changes in thermal perception according to physical, physiological and psychological processes. Particular care has to be taken in regard to the design of the control interface, as it can greatly inhibit the ability to control a device effectively.

In addition, users expressed the wish for a wider range of options of how to control a personal device including remote control but also smart device control, which would allow a device to adjust temperature based on environmental conditions and body temperature. To which extent smart temperature control can provide heating or cooling at the level needed to match individual perceptions and expected states of comfort requires further investigation. Research on the smart thermostat Nest suggests that smart features are not as effective as one might expect, which, however, depends on the ability of the system to correctly classify the user actions it learns from as well as to render its processes legible to the user (Yang & Newman 2013). Unlike smart home applications like the Nest, which operate on an environmental scale, smart wearable devices face additional challenges in as such as they are close to the body and therefore pose additional questions in regard to how far automation can go for a user to still feel comfortable and in control when changes occur.

Furthermore, personal heating and cooling needs to be readily available and its use should not require too much mental and physical effort. If too much effort was involved to ensure the availability of heating or cooling, the devices became present-at-hand rather than ready-to hand and their use as well as the focus on the actual work was affected (Heidegger et al. 2010; Dourish 2001). Thermal devices and applications for use in offices should consequently not hold centre stage of attention and remain “unmonopolizing” (Mann 1998).

To be functional our findings suggest that devices either need to provide a certain versatility and allow for adaptation or be tailored to parts of the body, which are key to the perception of thermal comfort. As feet are generally perceived as being colder than other body areas, cold feet are the major source of discomfort in cool environments and strongly impact perceived overall comfort (Arens et al. 2006a; Arens et al. 2006b). Applying heating to the feet is described as a way to enhance comfort, which is reflected in the positive response of participants to the heated socks. In turn, the head region including head, face and neck is the major source of discomfort in warm environments (Arens et al. 2006a; Arens et al. 2006b). The positive response to the cooling neck tie can be thus explained. But also the appropriation of devices partly followed this pattern, for example, in the use of different cooling devices on the head, face, or neck, or the heated shoulder pad over the legs. It came very naturally to participants to appropriate and use the devices according to their needs. We found that the more possibilities for appropriation and versatility the design of the devices afforded, the more varied was their use. This related to the real affordances of an object and the perceived affordances from the user’s perspective (Norman 1999) and regarded aspects of the physical design, such as the style, form and dimension. Portable devices afforded adaptation more intrinsically, as they did not predefine the application area per se.

Although we found that users appreciated flexible wearable solutions, overall preferences for solutions, which were not body-bound in nature, were expressed. Scepticism of wearable devices was more widespread for cooling devices, which might be due to the fact that human thermal perception is in general more sensitive to cooling and that the devices employed during the study were considered too cold (Arens et al. 2006b). However, aspects of acceptance and individual preferences in relation to on-body and off-body applications and uses in regard to personal devices provide an interesting area for further investigation from a design perspective.

In regard to the design of wearable devices, we also found that apart from versatility, aesthetics, materiality and comfort of wear as well as unobtrusiveness have to be taken into account, which corresponds to key design aspects defined by Rogers et al (2011). Participants showed an awareness of social implications and addressed concerns in regard to the intrusiveness and inconvenience of heating and cooling devices to others. Accordingly, participants expressed a preference for personal devices providing directed thermal output. This corresponds to the findings of a study on adaptation behaviour, which found that adjustments on a personal, local level, such as clothing are preferred by office workers over adjustments on a more global scale (Liu et al. 2014). Aesthetic and physical properties of wearable devices gain particular relevance once they are perceived as accessories or garments and the boundary to clothing and fashion is crossed and are key to the adoption of wearables (Wei 2014).

Limitations of the power supply affected the duration of use, mobility and flexibility as well as comfort of wear of the devices. However, it is to be expected that with ongoing technological progress, battery sizes will decrease, capacity increase and wearability and usability will be improved.

5.2. Limitations of the approach

In the scope of our studies we focussed on the usability of the devices as perceived by the users. One limitation of our approach is that participants were not exposed to all five devices available in the respective study but that they tested and used only one or a selection of the devices. This means that different participants tested different devices. In general, participants referred to the devices they had used when expressing their preferences, suggestions, likes and dislikes. Consequently, the exposure to and experience involved in using a particular device greatly affected the response.

In addition, we noticed that participants also referred to or reflected on their use of other known devices. Past experiences and exposures might therefore be the reason why preferred devices were not necessarily also referenced as the most usable and convenient devices for use in context. Fans, for example, are commonly available and accepted in offices on campus, which could explain why a personal cooling fan has been nominated most often as the preferred device for cooling. However, our approach does not explicitly address to what extend past experiences, past exposures, and expectations influenced the feedback and the expressed preferences of our participants.

Also, the technologies of the devices we chose might have impacted the expressed preferences of the participants. In partial accordance with this, participants stated that they would prefer other ways of cooling than ice packs, such as air flow or natural ways like evaporation, and suggested looking into other technologies to provide more stable, controllable, and less extreme cooling.

6. CONCLUSIONS

We presented the findings of two field studies of personal heating and cooling devices. The bottom up, inductive approach of deploying off-the-shelf personal devices into the wild helped us uncover usability issues of existing devices and raised questions centred on the use, application and design of personal solutions to thermal discomfort in the context of open-plan workplaces. We found that versatility, availability, control and location of use were key characteristics of more functional and effective devices, as they supported participants' adaptation to changing climatic and physiological conditions and thus helped address changing comfort needs. Although participants responded positively to personal solutions in general, we found differences in responses towards on-body and off-body solutions, in particular in the cooling case.

The key findings and aspects to take into account in the design and development of personal heating and cooling devices can be summarised as follows:

- **control**: the availability of temperature control, either locally and/or remotely and the availability of a range of temperature settings together with the adjustment of temperature levels as needed, manually and/or automated, on a clear, accessible and easy to use interface;
- **functionality and versatility:** designing for application, versatility, flexibility and mobility, which regards the location of use, the technology employed to provide heating or cooling as well as allowing for adaptation and appropriation by the user;
- **effectiveness and efficiency:** the ability to provide heating/cooling when needed (availability), where needed (location), in the amount needed (adjustability), as long as needed (reliability);
- **wearable design:** addressing the aspects of aesthetics, materiality, comfort of wear and the need for unobtrusiveness in the design for comfort;
- **individual preferences:** openness for the preference of individual users for on-body or off-body heating or cooling applications, as well as the preference for different body areas to apply heating or cooling to;
- **context of use:** designing for the context of use on a personal local level as well as taking into account spatial and social implications on a supra-local level;
- **power supply:** considering the usability trade-offs in deciding for battery, mains or USB as power supply in respect to the context of use, duration of use, comfort of wear and mobility.

The design requirements we identified based on our findings are widely reflected in the more broadly formulated challenges and issues in the development of wearable devices and technologies addressed by Rogers et al. (2011), Chan (2012) and Benyon (2014). However, as personal wearable or portable devices for thermal comfort are taking over environmental functionalities and are crossing the boundaries between fashion, technology and environment, body, sensations and perceptions, this requires paying more specific attention to the design for comfort, usability and user experience in context, than more generally defined frameworks cover.

The findings of the two studies here presented have informed further inquiries in this field and fed into the development of portable and wearable prototypes. Subsequent work has been conducted in particular looking at aspects of control and matters of affordance and versatility in the design of wearable and portable devices for personal heating and cooling. Although the context of use in our work has been limited to open-plan office spaces, a wider range of scenarios of use leading to further interesting applications in the area of comfort and well-being are conceivable.

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